QCD and String Theory

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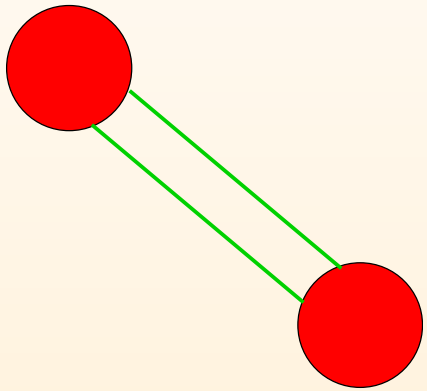
Origin of String Theory in the 60's: Regge trajectories of resonances

$J = \alpha' M^2 + \alpha_0$



Drawback of 4d String Theory: Tachyons

String Theory includes gravity in a natural way

70's: Success of QCD as theory of strong interactions

Today: New approaches which bring string theory and QCD closer together

AdS/CFT correspondence

AdS/CFT Correspondence

(Maldacena 1997, AdS: Anti-de Sitter space, CFT: conformal field theory)

- Quantum Field Theory $\Leftrightarrow$ Gravity Theory
- Duality: Quantum field theory at strong coupling
  $\Leftrightarrow$ Gravity theory at weak coupling
- Conformal field theory in four dimensions
  $\Leftrightarrow$ Supergravity Theory on $AdS_5 \times S^5$
- Arises from String Theory in a particular low-energy limit:
  't Hooft coupling $\lambda = g^2 N$ large and fixed , $N \to \infty$
- 4d field theory lives at the boundary of 5d Anti-de Sitter space
  ($\mathcal{N} = 4$ Super Yang-Mills)

New results, generalizations and applications

- Gravity dual descriptions of confining gauge theories
- Hard scattering, Pomeron — Polchinski, Strassler et al
- Finite-temperature field theories

  Quark-Gluon Plasma, Jet quenching — Son, Starinets et al
- Adding flavour to AdS/CFT — Karch/Katz
- Spontaneous chiral symmetry breaking — Evans, J.E., Guralnik et al

  Sakai+Sugimoto

  Non-perturbative calculation of meson spectra by solving 2nd order gravity equations of motion.
- AdS/QCD ('bottom-up approach') — Son et al, Brodsky, ...

AdS/CFT correspondence

- Anti-de Sitter space:

  Curved space with constant negative curvature and boundary

  Metric: $ds^2 = e^{2r/L}\,\eta_{\mu\nu}dx^\mu dx^\nu - dr^2$

- Symmetries coincide

  Isometries of AdS space $\Leftrightarrow$ Conformal group in field theory

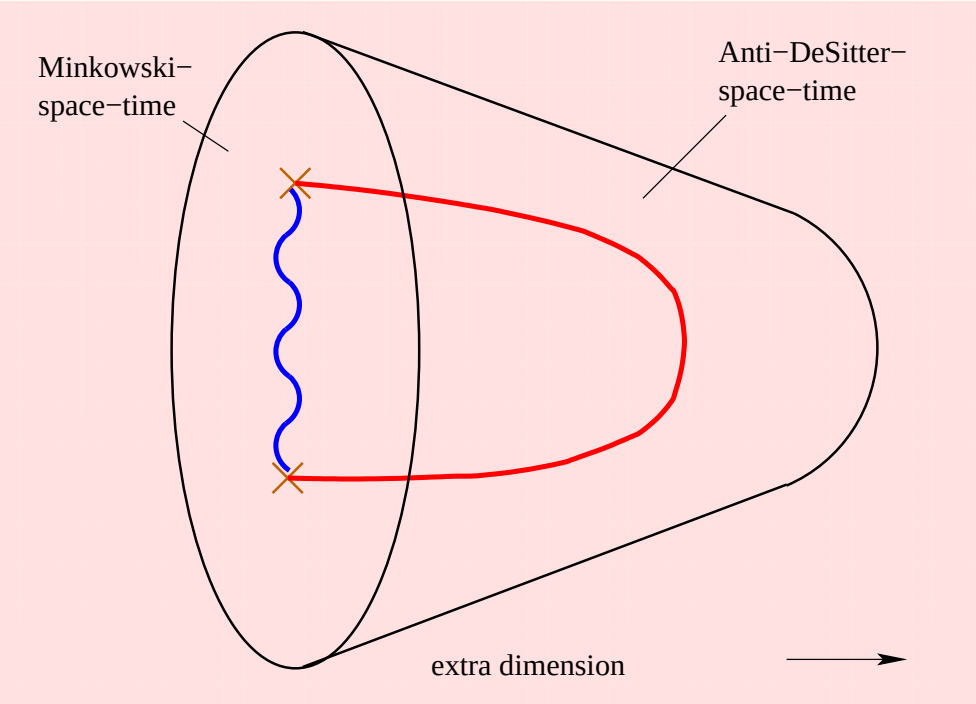
  Isometries of 5-Sphere $\Leftrightarrow$ R symmetry in field theory

- Dictionary:

  Field theory operators $\Leftrightarrow$ supergravity fields

  Quantum numbers coincide

AdS/CFT Correspondence



AdS/CFT correspondence:

Computation of conformal correlation functions for boundary theory

using propagation through AdS space

Holography

Field-operator correspondence:

Generating functional for correlation functions

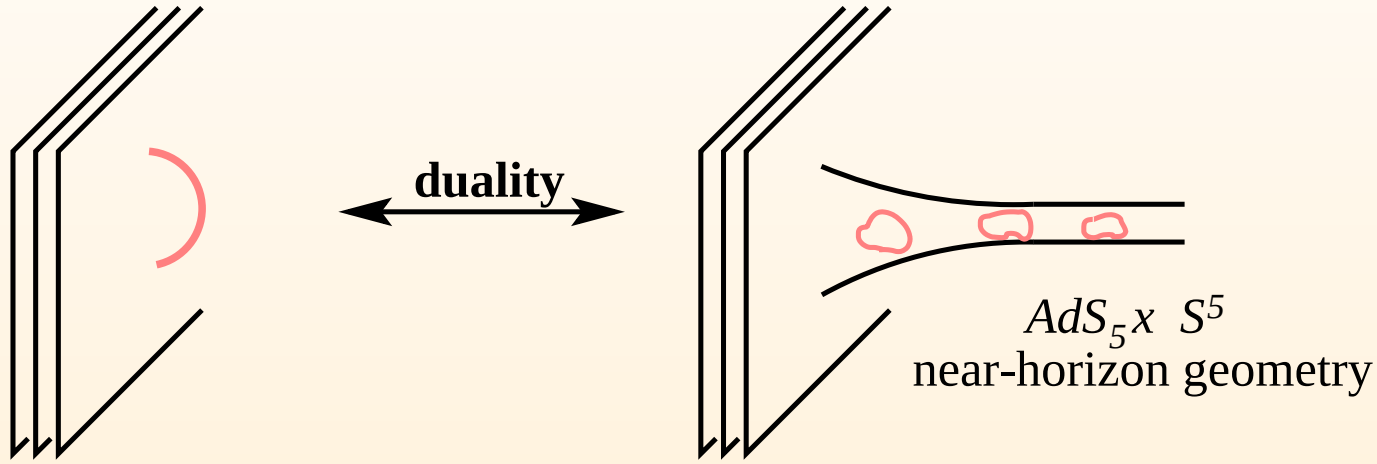
of particular composite operators in the quantum field theory

coincides with

Classical tree diagram generating functional in supergravity

String theory origin of AdS/CFT correspondence

D3 branes in 10d



$\Downarrow$ Low-energy limit

$\mathcal{N} = 4$ SUSY $SU(N)$ gauge theory in four dimensions ($N \to \infty$)

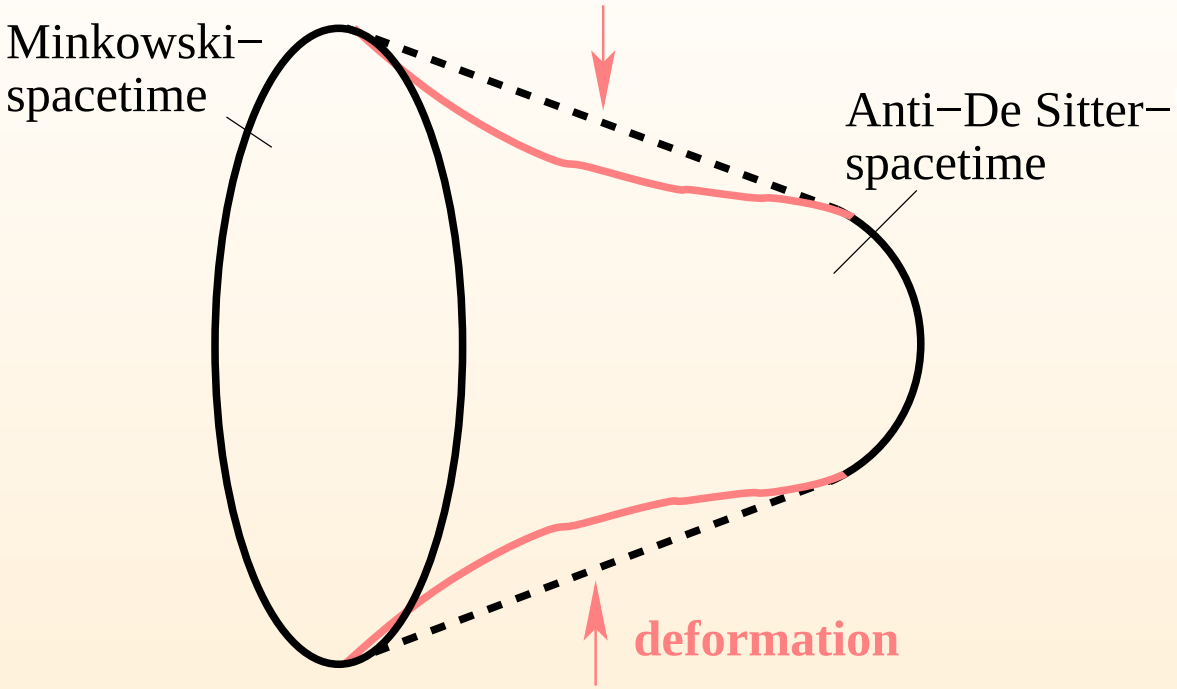
$\Leftrightarrow$

Supergravity on $AdS_5 \times S^5$

Generalizations of AdS/CFT

- Breaking of conformal symmetry and supersymmetry
  through deformations of the original $AdS_5 \times S^5$ space
- Adding flavor (quark fields in fundamental representation)
  through additional brane probes

Deformations of AdS space



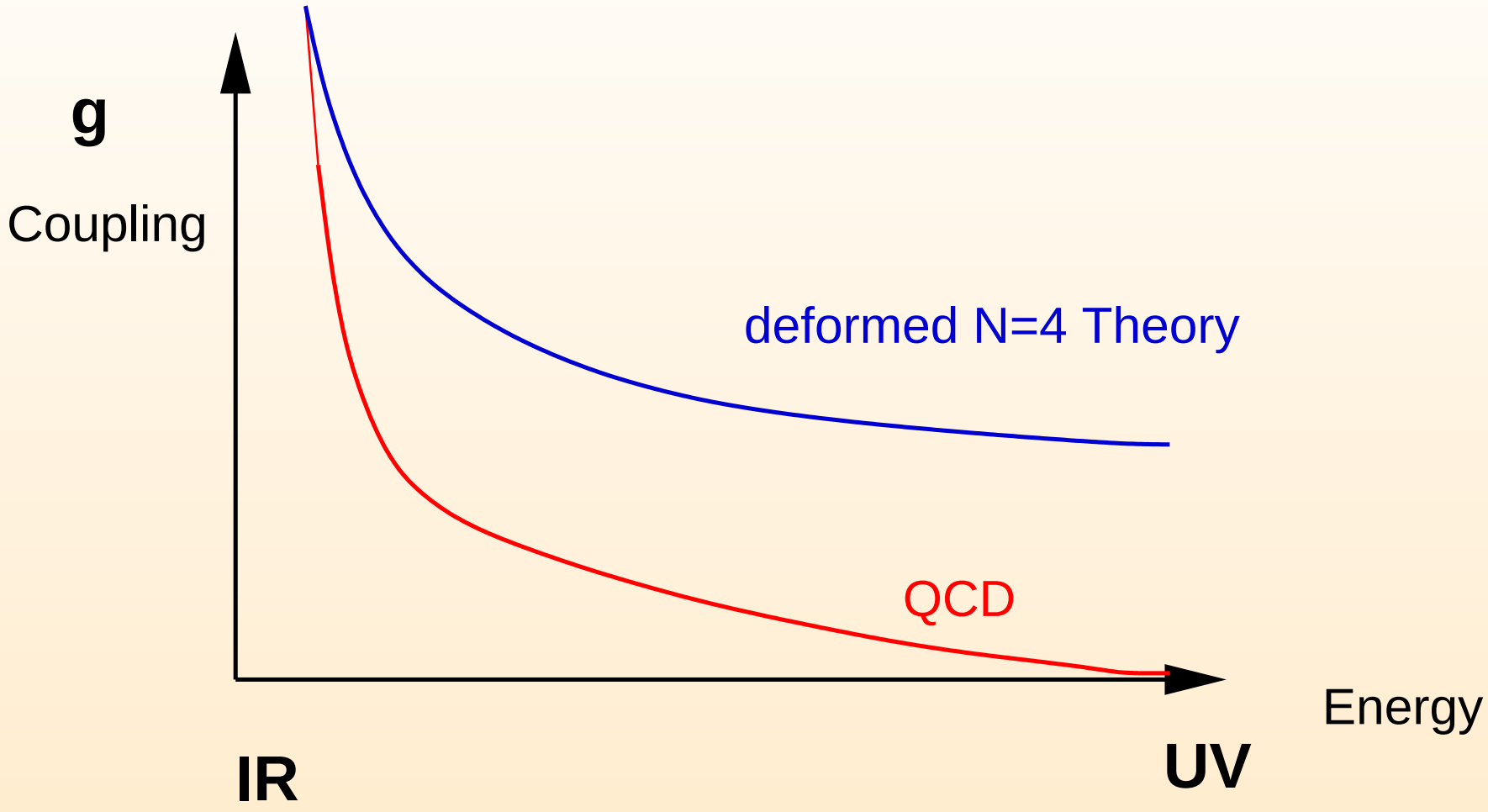
Fifth Dimension $\Leftrightarrow$ Energy scale

Renormalization group flow from supergravity

$\Rightarrow$ 'holographic' Renormalization Group flow

SUSY broken by deformation of S^5

Running gauge coupling



Brower, Polchinski, Strassler, Tan '06

Pomeron:

Coherent excitation that dominates hadronic elastic scattering

at large s, small t, large N

contributes the leading singularity in the angular momentum plane

Pomeron in AdS/CFT: (large N)

Calculation of field theory amplitude from string amplitude in ten-dimensional $AdS_5 \times S^5$ space with cut-off

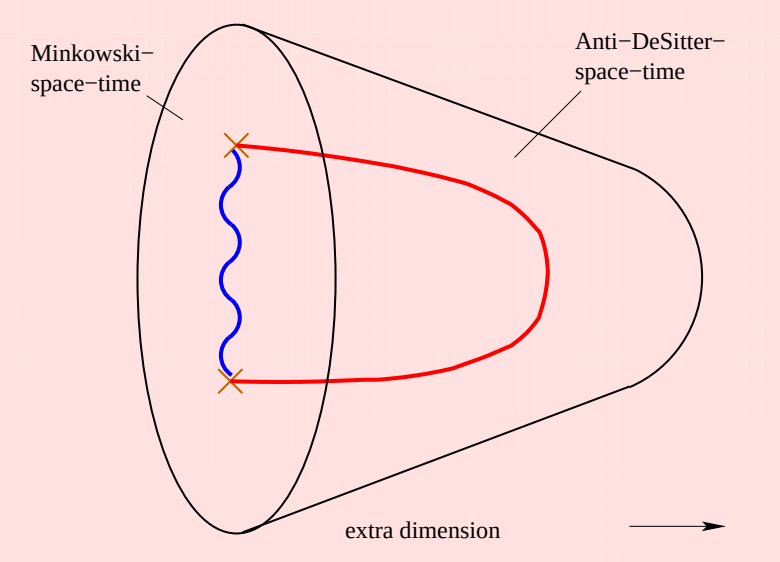
Four-dimensional scattering given by coherent sum over scattering in the six transverse dimensions

Hard scattering

Holographic encoding of gauge theory physics:

Low energy states at small r, high energy states at large r (near boundary)

Warped space:



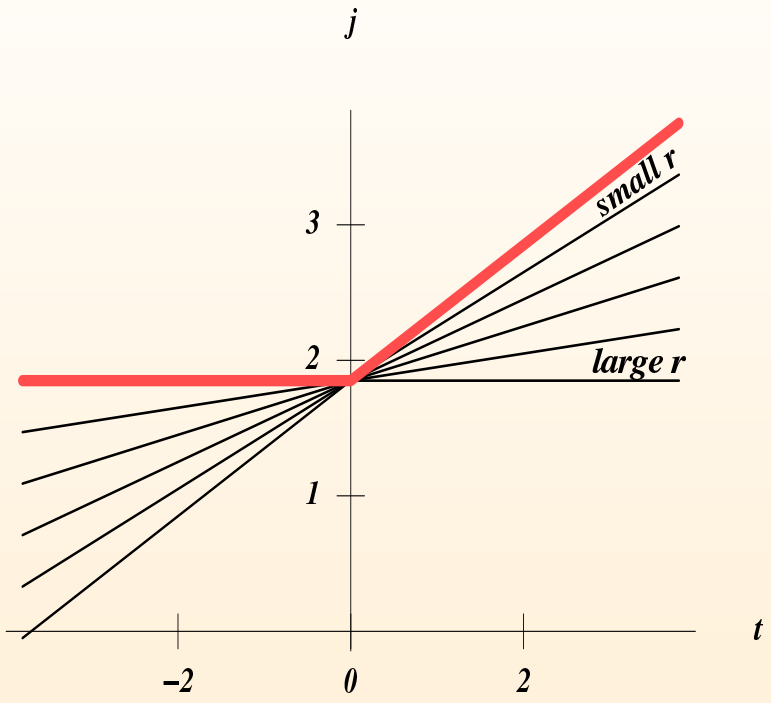
$$p_\mu = \frac{r}{L}\tilde{p}_\mu$$

$$\mathcal{A}(s,t) \propto s^{\alpha(t,r)}$$

p_μ conserved momentum, corresponding to invariance under translation of x^μ

$\tilde{p}_\mu$ momentum in local inertial coordinates for momenta localized at r

Pomeron in AdS/CFT



At large s, highest trajectory will dominate:

t positive: r small: soft (Regge) pomeron, properties determined by confining dynamics: glueball

t negative: r large: hard (BFKL) pomeron, two-gluon perturbative small object

Shear viscosity η from energy-momentum tensor $T_{\mu\nu}$

Kubo formula

$$\eta = \lim_{\omega \to 0} \frac{1}{2\omega} \int dt d^3x \, e^{i\omega t} \, \langle [T_{xy}(t,x) T_{xy}(0,0)] \rangle$$

$\langle [T_{xy}(t,x) T_{xy}(0,0)] \rangle$ obtained from propagation of graviton through AdS space

Policastro, Son, Starinets 2001

Result:

$$\frac{\eta}{s} = \frac{\hbar}{4\pi}$$

lower bound, s entropy density

Jet quenching

Jet quenching: medium-induced modification of high-p_T parton fragmentation

Medium-induced gluon radiation dominant over elastic scattering
at high parton energies

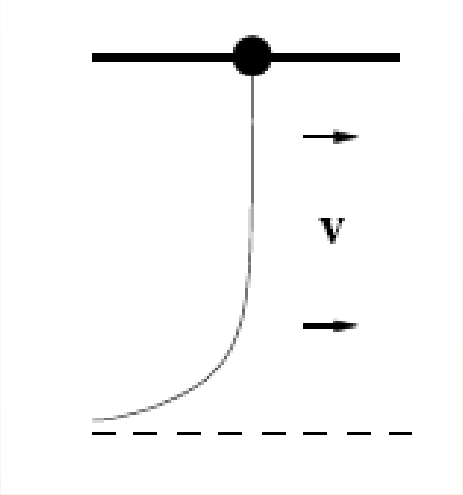
AdS/CFT descriptions:

1. Wilson loop

2. Drag force of heavy quark

Herzog, Karch, Yaffe et al
Liu, Rajagopal, Wiedemann
Gubser et al
(...), 2006

Jet quenching and drag force



Herzog, Karch, Yaffe, et al (...)

Drag force of heavy quark in the medium:

described by string moving through AdS with a black hole

Jet quenching parameter:

$$\frac{d}{dt}\langle(\vec{p}_\perp)^2\rangle = 2\pi\sqrt{\lambda}T^3$$

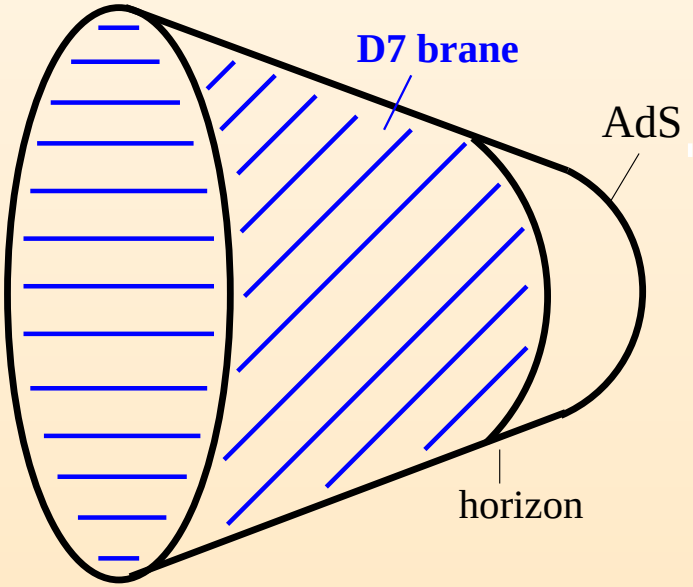
slightly smaller than suggested by RHIC data

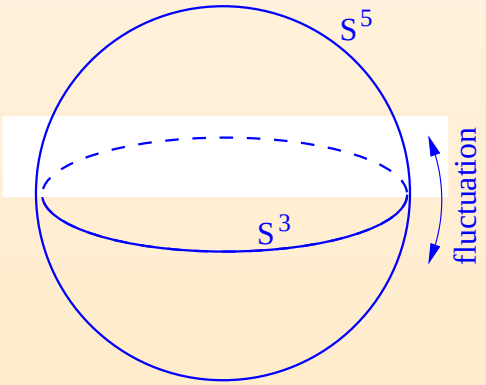
Quarks (fundamental fields) within the AdS/CFT correspondence

Karch, Katz
J.E., Evans et al
Myers, Mateos et al

D7 brane probe:

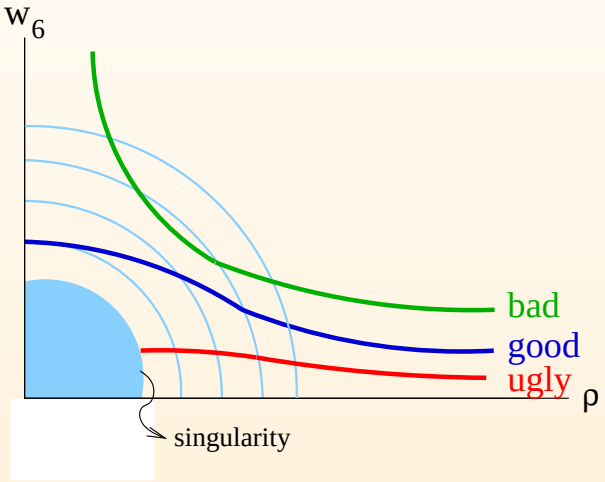
	0	1	2	3	4	5	6	7	8	9
D3	X	X	X	X						
D7	X	X	X	X	X	X	X	X		



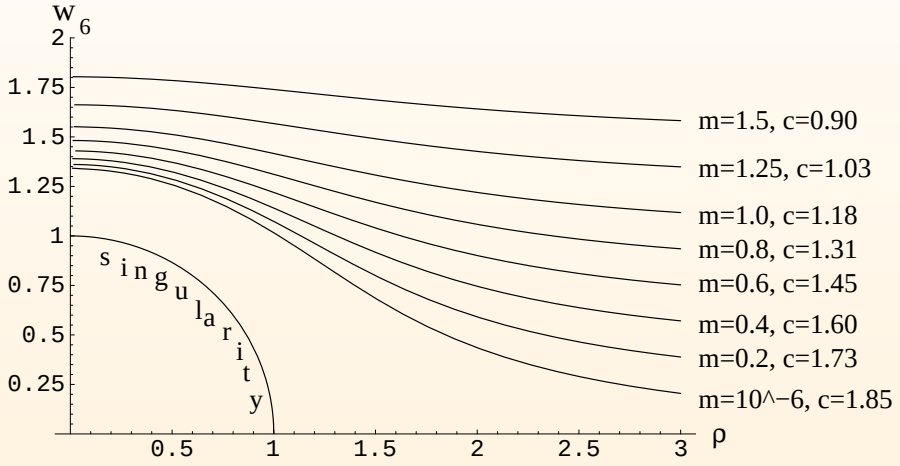


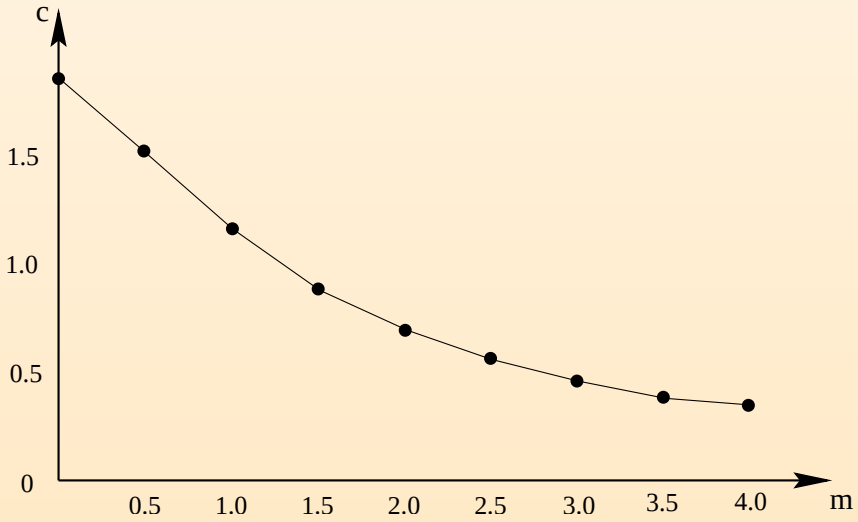
Chiral symmetry breaking

Solution of equation of motion for probe brane



Numerical Result:





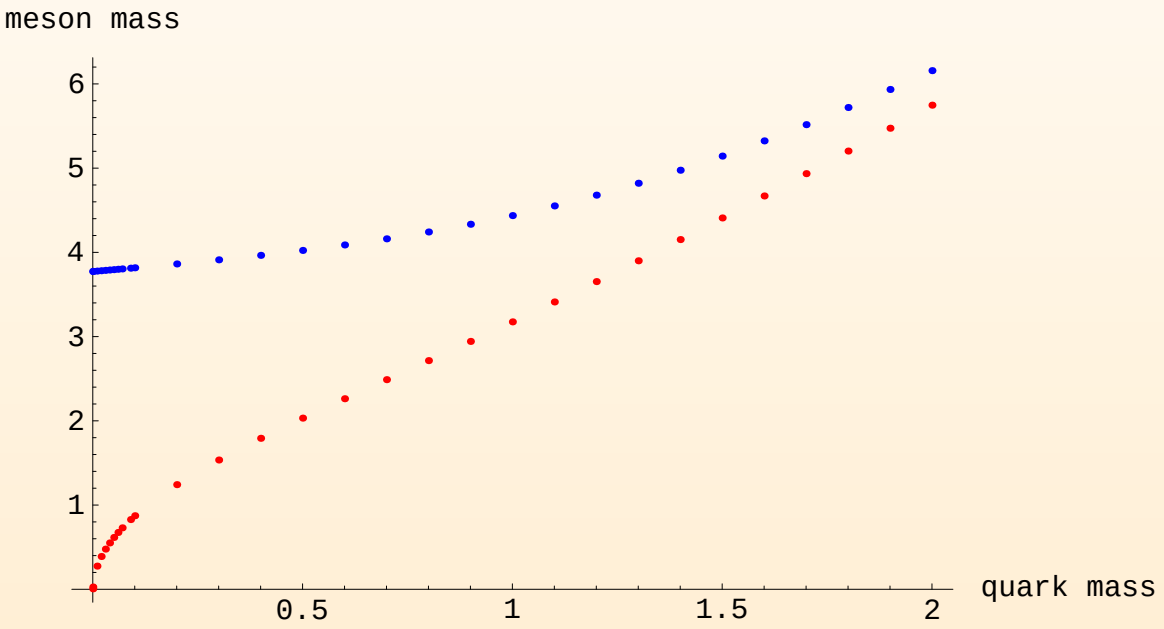
Result:

Screening effect: Regular solutions do not reach the singularity

Spontaneous breaking of $U(1)_A$ symmetry: For $m \to 0$ we have $c \equiv \langle \bar{\psi}\psi \rangle \neq 0$

Meson spectrum

From fluctuations of the probe brane: $\delta w = f(\rho)\sin(k\cdot x)\,, \qquad M^2 = -k^2$



Goldstone boson (η')

Gell-Mann-Oakes-Renner relation: $M_{Meson} \propto \sqrt{m_{Quark}}$

Vector and axial vector mesons

Sakai+Sugimoto 12/2004

$D4/D8/\bar{D}8$ brane model

vector and axial vector mesons ρ and a_1, meson mass ratio

Experiment/lattice:

$$\frac{m_{a_1}^2}{m_\rho^2} = \frac{(1230MeV)^2}{(776MeV)^2} = 2.51$$

Stringy model:

$$\frac{m_{a_1}^2}{m_\rho^2} = 2.4$$

Conclusions

- AdS/CFT correspondence provides new tools
  for addressing problems within QCD

  – Hard scattering
  – Quark-Gluon plasma
  – Chiral symmetry breaking and mesons

- New relations between string theory and QCD are expected to trigger
  further new developments in both fields -

  eventually bringing the two fields even closer together.